THE USE OF UHPC FOR PRECAST BRIDGE DECKS: THE TECHNOLOGY, APPLICATIONS and CHALLENGES FACING COMMERCIALIZATION

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ABSTRACT:

The material technology presented is an ultra-high performance, fiber-reinforced concrete that offers ductility, durability, aesthetic flexibility and superior strengths (compressive strength up to 30,000 psi and flexural strength up to 6,000 psi). Many economies gained are a result of engineering new solutions for old problems. By utilizing the unique combination of properties, designers can create longer spans that are thin, lighter and more graceful, with improved durability and impermeability against corrosion, abrasion and impact. Additionally, designs can eliminate passive reinforcing steel and experience reduced global construction costs, formworks, labor and maintenance; relating to improved site safety, speed of construction and extended usage life.

This paper presents the properties, research, design assumptions, prototyping, manufacturing, installation and assembly procedures for specific precast bridge deck systems and projects – as well as a global look at projects around the world.

Keywords: Abrasion, Aesthetics, Composite, Ductile, Durability, Fiber-reinforced, Impact, Impermeability, UHPC, Usage-life

INTRODUCTION

According to the Federal Highway Authority (FHWA) National Bridge Inventory Study, approximately 180,000 bridges in the USA are structurally deficient or obsolete, with more than 3,000 new bridges added each year. State, provincial and municipal bridge engineers are seeking new ways to build better bridges, thereby reducing maintenance costs which are diverted from capital budgets required for building much needed new highways and bridges to reduce travel times. This issue is of such a concern that the FHWA launched a program called “The Bridge of the Future”, to help drive new solutions for building bridges.[1]

One new technology being developed to help solve North America’s deteriorating bridges is an ultra-high performance, fiber reinforced cement composite material which offers superior technical characteristics including ductility, strength, and durability while providing highly moldable products with a high quality surface aspect.

This innovative and unique combination of properties enables designers to create thinner sections and longer spans that are lighter, more graceful and innovative in geometry and form while providing improved durability and impermeability against corrosion, abrasion and impact. Many of the economies gained from this technology are a result of engineering new solutions to old problems. The material technology permits it to be used without passive reinforcing (rebar) while reductions in formwork, labor and maintenance further add to economy. The elimination of rebar improves safety, reduces weight and speeds up construction while the improved durability reduces maintenance and extends the usage-life.

This paper presents the material technology, potential uses and examples of projects and prototypes for the bridge market.

THE MATERIAL CHARACTERISTICS OF THE TECHNOLOGY

The material offers a unique combination of technical characteristics including ductility, strength and durability, while providing highly moldable products with a high quality surface. It is a high-strength, ductile material formulated of constituent materials including portland cement, silica fume, quartz flour, fine silica sand, high-range water reducer, water, and steel or organic fibers. The technology is covered by one of many patents in a range of ultra-high performance concretes, all under the material’s trademark[2]. Compressive strength for bridge applications range up to 30,000 psi and flexural strengths of up to 6,000 psi.

The high mechanical properties are a result of proportioning the constituent materials to produce a modified compact grading and the fiber geometry (1/2-inch x 0.008-inch diameter) to nominal maximum coarse aggregate size of 0.02 inches[3].

The ductile behavior of this material is a first for concrete, with the capacity to deform and support flexural and tensile loads, even after initial cracking (Figure 1). These performance characteristics are the result of improved micro-structural properties of the mineral matrix, especially toughness and control of the bond between the matrix and the fiber.

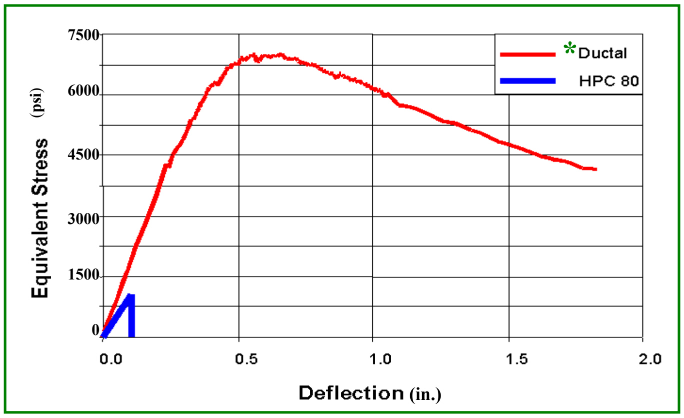


Fig. 1 Load-Deflection Curve for prisms loaded in 4-point bending[4]

*Ductal® by Lafarge prisms cured at 195° with 2% fibers by volume. "HPC 80" is High Performance Concrete with 80 MPa (1100 psi) compressive strength.

There is almost no carbonation (depth penetration of <0.02 inches) or penetration of chlorides or sulphides and a high resistance to acid attack. The superior durability characteristics are due to a combination of fine powders, selected for their relative grain size (maximum 0.02 inches) and chemical reactivity. The net effect is a maximum compactness and a small, disconnected pore structure.

Following thermal treatment of 195° Fahrenheit for 48 hours, the material becomes dimensionally stable, with a creep coefficient of 0.2 and no post treatment shrinkage, thus making it very suitable for prestressed applications. The use of this material for construction is simplified through the elimination of reinforcing steel and its ability to be virtually self-placing or dry-cast. The following is an example of the range of material characteristics for a formulation with steel fibers[4]:

Strength[5]	**Mean Values**	**Durability[5]**	**Mean Values**
Compressive	20,000-30,000 psi	Freeze/thaw (after 300 cycles)	100%
Flexural	3,500-6,000 psi	Salt-scaling (loss of residue)	<0.0025 lb/ft^2
Youngs Modulus (E)	8-8.5 x 10^6psi	Abrasion (relative volume loss index)	1.2
		Oxygen permeability	<10^{-19}/ft^2
		CI permeability (total load)	<10
		Carbonation depth	<0.02 inches
		Chloride ion diffusion (CI)	0.02 x 10^{-11}ft^2/s

The materials are normally supplied to the precaster in a three-component premix. Powders pre-blended in bulk-bags, superplasticizer and fibers. Each premix is customized to provide the required mechanical properties and handling characteristics suitable for the casting and forming techniques.

To date, this material has only been used primarily in precast applications. Due to the mixing requirements, casting techniques, shrinkage characteristics during setting and curing, further development work is required prior to using for cast-in-place applications.

POTENTIAL USES

The development of this technology for the bridge market has been ongoing for approximately 10 years, with the first industrial use in 1997 for a pedestrian bridge in Sherbrooke, Quebec.

Many potential uses of this material for bridges are focused on areas where improvements can be made, such as: speed of construction, reducing maintenance, improving grade/alignment and extended usage-life of the bridge.

Table 1. List of Potential Uses of this Technology for Highway Bridges

	Description	**Advantages**
New Construction:		
- Composite deck-beams - Precast decks - Stay-in-place deck forms	- Pi-girders - Modular panels - Partial deck modular form panels	- addresses deck corrosion - speed of assembly - longer span/depth - improves grade alignment
Repair & Renovations:		
- Beams - Precast decks - Stay-in-place deck forms	- AASHTO or similar shapes - Modular Panels - Partial deck modular form panels	- addresses deck corrosion - speed of assembly - longer span/depth - improves grade alignment

EXAMPLES OF BRIDGE PROJECTS COMPLETED

The implementation of new technologies in the bridge sector has proven to be a long process due to the conservative nature of this segment. Highway bridge engineers, bestowed with guardianship of public money and safety, have always taken the position of demonstrating the technology before using it. One way to introduce a new technology to bridges is to first validate the technology in the pedestrian bridge market where architecture is more of a driver.

PEDESTRIAN BRIDGES

Since 1997, several pedestrian bridges have been constructed (globally) utilizing this material technology -- in Canada, France, Korea and Japan.

The Sherbrooke Bridge, Quebec, Canada (Figure 2) crosses the Magog River with a span of 180 feet. This space truss was precasted in 6 segments of 30 feet each, its top deck is 1¼-inch thick and the diagonals are formed with stay-in-place stainless steel tubes containing tri-axially confined UHPC with post-tensioning.[6]

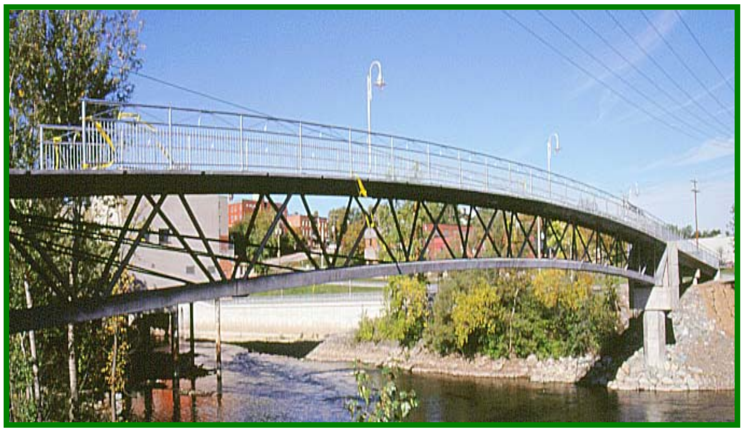
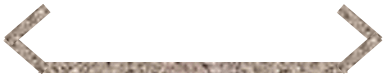


Fig. 2 Sherbrooke Pedestrian/Bicycle Bridge

While this material has significantly higher flexural-tensile capacity compared to normal and high performance concrete, prestressing further enhances the tensile capacity. Due to the lightness of the superstructure, the designers completed a dynamic analysis and in-situ testing which validated the mathematical model.

The Chryso Plant Footbridge (Figure 3), precasted by Bonna Sabla of France, features a walkway (5-ft-3-in wide by 62-ft long) constructed without any prestressing or passive reinforcing steel. The cross section is an inverted U-shape with sloping horizontal V-sides. The design replaced an original concept of wood and steel, offering six times greater load resistance than the required standards, with a deck that is only 3¼-inches thick.

Figure 3 – Footbridge in Chryso Plant, Sermaise, France



Cross-section of Sermaise Pedestrian Bridge

The “Footbridge of Peace” in Seoul, Korea (Figure 4), was inaugurated in April 2002 and has a clear span of 400-feet x 14-feet wide, with a 1¼-inch deck. Designed by French architect Rudy Ricciotti, it features an elegant, high arch with 6 precast segments, post-tensioned together. The post-tensioning provides the connection between the 6 segments and supplements the tensile capacity in the unbalanced load condition.[7]

Fig. 4 The Seonyu Footbridge in Seoul, Korea

In October 2002, Japan built its first pedestrian bridge with UHPC. The Sakata Mirai Footbridge (Figure 5) is a 164-foot long by 8-foot wide trapezoidal voided web box girder. The 8-segment precast bridge was post-tensioned.

Fig. 5 The Sakata Mirai Footbridge in Sakata, Japan

A second footbridge constructed in Yamagata prefecture, Japan, was completed in January 2004. The Yokemuri Footbridge (Figure 6) is a square box girder frame with a span 116-feet by 11-feet, 6-inches wide and an overall height of 3-feet, 1-inch. The construction was completed by Taisei, utilizing a pre-mix from Taiheiyo Cement Corporation[8].

Fig. 6 The Yokemuri Footbridge in Yamagata, Japan

HIGHWAY BRIDGES

While the introduction of this technology has proceeded much faster in pedestrian bridges compared to highway bridges, there have been highway-bridge projects constructed.

The "Shepherds Bridge" (Figure 7), erected 100 miles north of Sydney (Australia), replaced an old, obsolete timber bridge. It measures 69 feet wide and spans 49 feet, 2-inches. Sixteen girders (I-shaped) made of UHPC support a 6-foot, ¾ inch thick reinforced concrete slab, cast in-place set over the girders. This bridge was designed and built by VSL-Australia, for the Australian RTA (Roads and Traffic Authority), to provide durability, strength and a reduced maintenance cost. I-girders are $23^5/_8$ inches in depth, weighing only 188 pounds per lineal foot, are spaced at 4-feet, 3-inches on center and contain no passive reinforcing steel. The full shear capacity is carried by the tensile properties of the material. The bridge was designed for "T44" and "HPL320" truck loading (similar to AASHTO HL93), complying with Australian road requirements.[9]

Fig. 7 Shepherds Bridge, NSW, Australia

In 2000, the FHWA began investigating UHPC as a possible solution to replace deteriorating highway bridges in the USA. Early work investigated the relative performance of UHPC girders without passive reinforcing steel for shear and the durability properties possible for decks due to the low porosity and impermeability against the ingress of chlorides, thereby having potential to significantly increasing the life of a bridge deck. Early testing proved positive for the FHWA and further work was undertaken through a cooperative R&D program at MIT. The focus of the work at MIT was to determine the optimum way to use UHPC for bridge construction.[10]

The collaborative work at MIT lead to the development of a pi-girder profile (Figure 8) for a typical 2-lane, 2-span highway bridge, which represents nearly 75% of bridges built on the USA highway system. This pi-girder was designed based on the AASHTO LRFD Bridge Design Specifications to carry the HL-93 load configurations. This 2-foot-9-inch overall deep pi-girder section is designed to span up to 110-feet with a 3-inch, unreinforced integral deck.

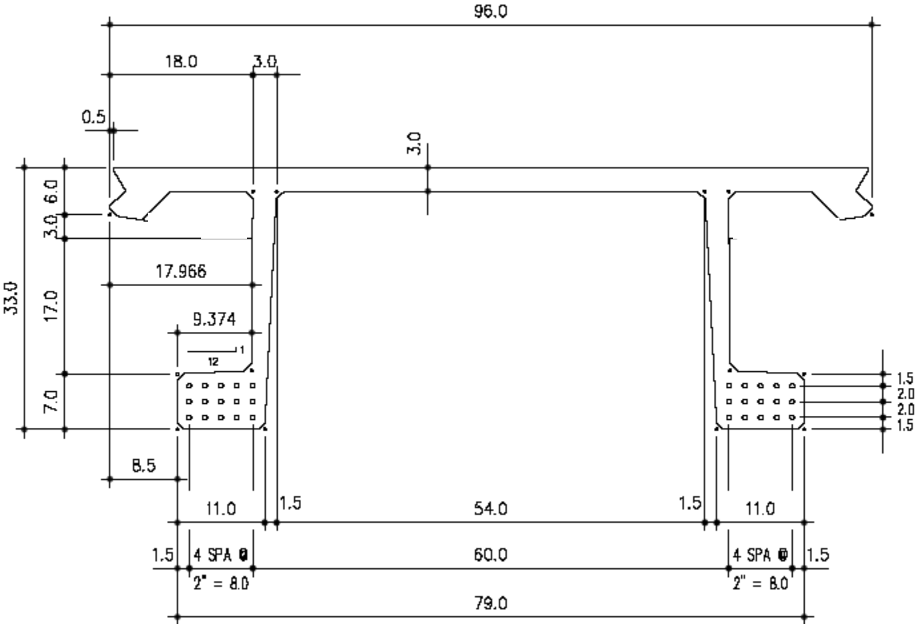


Fig 8 Cross-section of MIT/FHWA Pi-girder (imperial units – inches)

In 2003, the FHWA engaged Prestress Services of Lexington, KY to manufacture the pi-girders (Figures 9-a and 9-b). The precast pieces were then transported to the FHWA's Turner-Fairbank Laboratory to be installed in a test track (Figure 10) for long-term testing and full destructive testing.

Fig. 9a Pi-girders at Prestress Service, Lexington, KY

Fig. 9b Pi-girders at Prestress Service, Lexington, KY

Fig. 10 Installing pi-girders at the FHWA Turner-Fairbank Laboratory

Two USA DOTs have also begun programs to introduce UHPC bridge girders into their highway programs – Virginia and Iowa[11]; both introducing the use of this material for girders as a validating interim step to developing higher performing bridges with unreinforced UHPC in the decks.

OTHER POTENTIAL FOR BRIDGES

To date, the use of this technology in bridges has introduced the material to engineers and enabled highway officials to visualize a few of the benefits. The removal of passive reinforcing steel provides a significant flexibility for designing innovative, more refined shapes and eliminates the basic weakness with reinforced concrete decks that eventually leads to failure of the deck. This technology has the ability to significantly alter the way bridge decks are constructed.

This technology (for pedestrian bridges) provides architects and engineers a large degree of freedom to design new and innovative shapes that were not possible before. Figure 11 shows a single bulb-tee concept which is currently being evaluated for a pedestrian bridge project in Calgary, Alberta, Canada.

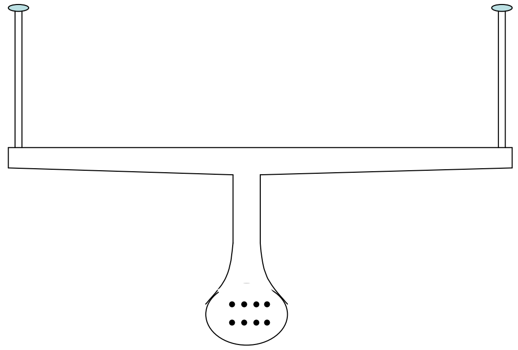


Fig. 11 Cross-section of a single bulb-tee pedestrian bridge

For highway bridges, two other promising uses of this technology are for full depth precast deck panels and for stay-in-place thin deck forms in steel-free bridge decks (Figure 12).

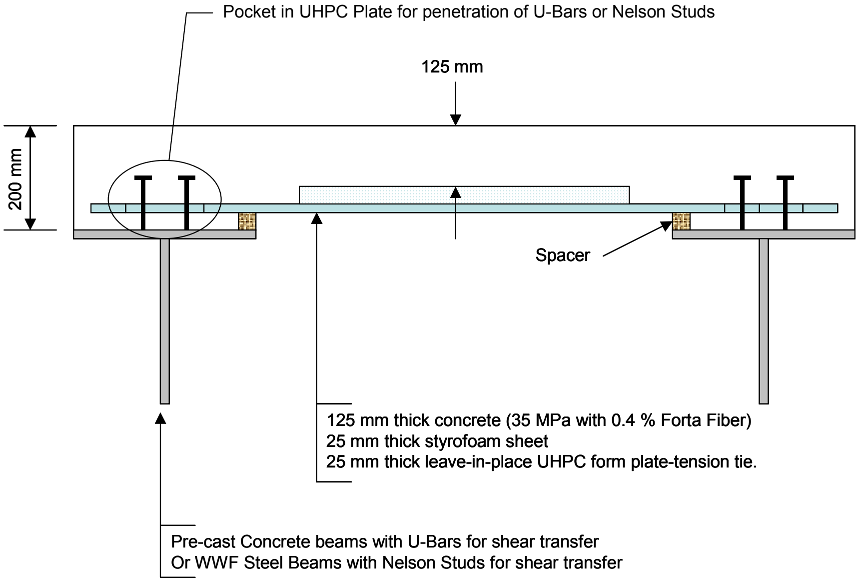


Fig 12 Section through a stay-in-place UHPC form on a steel-free bridge deck

CODES, STANDARDS AND DESIGN GUIDES

One challenge facing highway bridge engineers today is: how to design bridges with this technology when the current design codes/standards do not provide design guidance for materials with ultra-high mechanical properties. However, there has been progress by several groups in recent years to develop interim design guides to assist engineers.

FRANCE

Commencing in March 1999, at the request of the Association of French Civil Engineers (AFGC) Scientific and Technical Committee, an interim design guide was prepared for use with ultra-high performance fiber reinforced concrete (UHPRFC) for structures. The *Interim Recommendations* were published in both French and English in January 2002[12]. This 3 chapter and 9 annex document follows the design philosophy of the French concrete code Béton Armé aux Estate Limites (BAEL) 91, the French code for reinforced concrete and Beton Précontraint aux Estats Limites (BPEL) 91, the French code for pre-stressed concrete, revised 1999. A supplemental guide, to explain the BAEL 91 and BPEL 91, was also published in March 2003.

JAPAN

In September 2004 the Japan Society for Civil Engineers released "Recommendations for the Design and Construction of Ultra High Strength Fiber Reinforced Structures, - Draft"[13]. This 14-chapter document (with ten Appendices) provides guidance for designers on: design rules, allowable material properties for design, testing, durability, construction methodology and examples of completed Japanese bridge projects. While currently only available in Japanese, the document is being translated to English.

AUSTRALIA

At the request and with the support of VSL (Australia), the University of New South Wales, Australia published a "Design Guide for RPC Prestressed Concrete Beams" consistent with the design philosophy of the Australian code AS3600-1994[14]. This 14-chapter document (with 2 Appendices) provides design examples and material design guidance for compressive, flexural, shear and torsion strength. Also included are: recommended flexural crack control limits, deflection control, fire performance, fatigue, pre-stress losses and guidance on anchorage zones.

USA

Building on UHPC R&D work started at MIT in 1999, in parallel with work commenced at the FHWA in 2000 on the potential use of UHPC for bridges, in 2002 the FHWA engaged MIT to prepare a study on the optimization of UHPC for highway bridges. This collaboration lead to the release of a civil engineering report CEE Report R03-01 entitled "Model-Based Optimization of Ultra-high Performance Concrete Highway Bridge Girders[15]. The document presents a model-based design strategy for a brittle-plastic composite matrix with elasto-plastic composite fiber reinforcement. This 6-chapter document provides material models, model validation, an optimization process and suggested design formula. The guide provides a comparison between the model, based on a maximum crack width opening, and the LRFD design.

CHALLENGES TO IMPLEMENT THIS TECHNOLOGY

The applications/projects completed with this technology (to date) demonstrates that the manner in which the material is used is different than current uses of concrete, steel and other materials.

There has been an intentional slow/methodical, incrementally progressive development of this new material technology into the bridge market since the mid-1990's. Due to the justifiably conservative nature of this market, it is imperative to build a database from prototype projects that solve challenges, validate and build know-how on each of the areas of material properties, design, manufacturing, handling, erection and long-term serviceability. Each of the projects/prototypes undertaken have been selected to address various aspects of each of these challenges.

While there are still several challenges to implementing this technology, the real challenge ahead is to find the optimized shapes for each use. When this is determined, precasters, manufacturers and contractors can invest in the formworks to produce optimized pieces. The true economics of these systems will eventually bring value to the highway users in the standard mass production of optimized shapes.

CONCLUSION

The material's combination of properties (strength, durability, ductility, aesthetics plus design flexibility) facilitate architect's and engineer's abilities to create new optimized shapes for bridge construction. Overall, it offers solutions with advantages such as: speed of construction, improved aesthetics, superior durability and impermeability against corrosion, abrasion and impact, which translates to reduced maintenance and a longer life span for the structure.

Several of the completed projects presented are the first use of this material for bridges. While these examples demonstrate many of the potential benefits of the material technology, it is apparent that the true benefits are not yet fully recognized or realized. Furthermore, the optimized profiles and use of the material technology is still in its infancy and, in the next few years, much progress is anticipated in the area of optimized solutions.

Further project developments with this technology in other market segments should demonstrate and validate its value.

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